AFRL-AFOSR-UK-TR-2013-0049

Power and efficiency scaling of fiber OPO around 700 to 850 nm and Power-scaling of high coherence fiber Raman amplifiers

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EOARD Grant 11-3088

Report Date: October 2013

Final Report from 23 August 2011 to 9 May 2013

Distribution Statement A: Approved for public release distribution is unlimited.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
18 October 2013	Final Report	23 August 2011 – 9 May 2013

4. TITLE AND SUBTITLE

Power and efficiency scaling of fiber OPO around 700 to 850 nm and Power-scaling of high coherence fiber Raman amplifiers

5a. CONTRACT NUMBER

FA8655-11-1-3088

5b. GRANT NUMBER

Grant 11-3088

5c. PROGRAM ELEMENT NUMBER

61102F

6. AUTHOR(S)

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Jayanta K. Sahu

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Southampton
Optoelectronics Research Centre
University Road
Southampton SO17 1BJ UNITED KINGDOM

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515
APO AE 09421-4515

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/AFOSR/IOE (EOARD)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-AFOSR-UK-TR-2013-0049

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

For the first time, fiber Raman lasers produced near-infrared wavelengths from directly diode-pumped by high-power multimode diode sources and on a fiber OPO at red wavelengths. The fiber Raman laser reached 20 W of output power at 1019 nm, pulsed operation at 835 nm, and $M^2 = 2$ at 1019 nm from a double-clad fiber Raman laser. These three results are all world records or world firsts. It was also found that the fiber OPO suffers from below-par gain at the anti-stoles wavelength of ~718 nm. An OTDR is constructed to see how the 718 nm power evolves in the gain fiber. This is likely the first time this has been done. We find that the power grows exponentially for the first part of the fiber. After that, the growth is much slower. Even in the high-growth part, the gain is only ~10% of what theory predicts. The reason for this is unclear, but we suspect it is caused by fiber longitudinal fiber variations, which modify the dispersion and therefore disrupt the phase-matching. Attempts to control the dispersion by heating a section of the fiber showed that the conversion did change, but for the worse rather than for the better in these preliminary attempts.

15. SUBJECT TERMS

EOARD, Raman fiber lasers, high power raman fibers, directed energy

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			John Gonglewski
UNCLAS	UNCLAS	UNCLAS	SAR	22	**19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)1895 616007

Final report, EOARD award FA8655-11-1-3088 / FA8655-11-1-3088

"Power and efficiency scaling of fiber OPO around 700 to 850 nm" *and* *"Power-scaling of high coherence fiber Raman amplifiers"*

Date: Oct 18 2013

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Abstract

We report results on fiber Raman lasers at near-infrared wavelengths directly diode-pumped by high-power multimode diode sources and on a fiber OPO at red wavelengths. With the fiber Raman laser we reach 20 W of output power at 1019 nm, pulsed operation at 835 nm, and $M^2 = 2$ at 1019 nm from a double-clad fiber Raman laser. These three results are all world records or world firsts. We find that the fiber OPO suffers from below-par gain at the anti-stoles wavelength of ~718 nm. An OTDR is constructed which allows us to see how the 718 nm power evolves in the gain fiber. We believe this is the first time this has been done. We find that the power grows exponentially for the first part of the fiber. After that, the growth is much slower. Even in the high-growth part, the gain is only ~10% of what theory predicts. The reason for this is unclear, but we suspect it is caused by fiber longitudinal fiber variations, which modify the dispersion and therefore disrupt the phase-matching. Attempts to control the dispersion by heating a section of the fiber showed that the conversion did change, but for the worse rather than for the better in these preliminary attempts. The work was carried out under FA8655-11-1-3088 and FA8655-11-1-3088 P00001.

List of abbreviations and acronyms

APD	Avalanche photodetector
AS	Anti-Stokes
cw	Continuous wave
DCRF	Double-clad Raman fiber
DM	Dichroic mirror
FBG	Fiber Bragg grating
FRL	Fiber Raman laser
FWHM	Full width at half maximum
FWM	Four wave mixing
GRIN	Graded-index
HR	High reflectivity
HT	High transmittance
IR	Infrared
MM	Multimode
MOPA	Maser oscillator – power amplifier
NA	Numerical aperture
NIR	Near infrared
OC	Output coupler
OPO	Optical parametric oscillator
ORC	Optoelectronics Research Centre
OTDR	Optical time domain reflectometry
PGF	Parametric gain fiber
PRF	Pulse repetition frequency
QCW	Quasi-continuous-wave
SMF	Single mode fiber
SPM	Self phase modulation
SRS	Stimulated Raman scattering
VBG	Volume Bragg grating
WDM	Wavelength division multiplexing
Yb	Ytterbium
YDF	Ytterbium-doped fiber
YDFA	Ytterbium-doped fiber amplifier

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1. Introduction

This report describes the work carried out by the Optoelectronics Research Centre at the University of Southampton under two awards, FA8655-11-1-3088 and the continuation award FA8655-11-1-3088 P00001. The Period of Performance is Aug 11 2011 – May 9 2013.

The awards are both formally for "Power and efficiency scaling of fiber OPO around 700 to 850 nm", however, as proposed, the continuation award focuses on "Power-scaling of high coherence fiber Raman amplifiers". There is also a smaller part on the fiber OPO. This builds on the previous work "Fiber optical parametric oscillator and amplifier for high power, high efficiency operation at around 0.8 μm" (award FA8655-08-1-3013).

Part A, Power-scaling of high coherence fiber Raman amplifiers

2 (A). Approach and objectives

While this work originally targeted pumping with high-power disk-lasers and fiber lasers, it was refocused to direct diode-pumping to take advantage of new high-power, high-brightness multimode laser diodes. The diodes were then used to pump commercial, experimental, and in-house fiber Raman converters of different description. The work was co-funded by the EPSRC Centre for Innovative Manufacturing in Photonics (EP/H02607X/1), e.g., as it comes to fiber fabrication.

3 (A). Results, findings, accomplishments

The diode power is one order of magnitude or more smaller than that available from disk lasers and fiber lasers, but we still have three important results.

- Shortest-wavelength diode-pumped fiber Raman device of any description (835 nm).
- First cw fiber Raman device pumped directly by high-power multimode diodes source (1019 nm)
- First double-clad fiber Raman device pumped directly by high-power multimode diodes source (1019 nm, cw)

The pulsed results 835 nm have been presented at conferences [1] and have also been accepted for publication in JOSA B [2]. We consider the cw results at 1019 nm to be more interesting results and indeed breakthroughs, and to date only preliminary results have been published [3]. Therefore, this report focuses on those results.

<u>The main point is that the technology is now ready for scaling to the multi-kW regime of this extremely promising approach.</u>

Fig. 1 shows the experimental setup for cw pumping.

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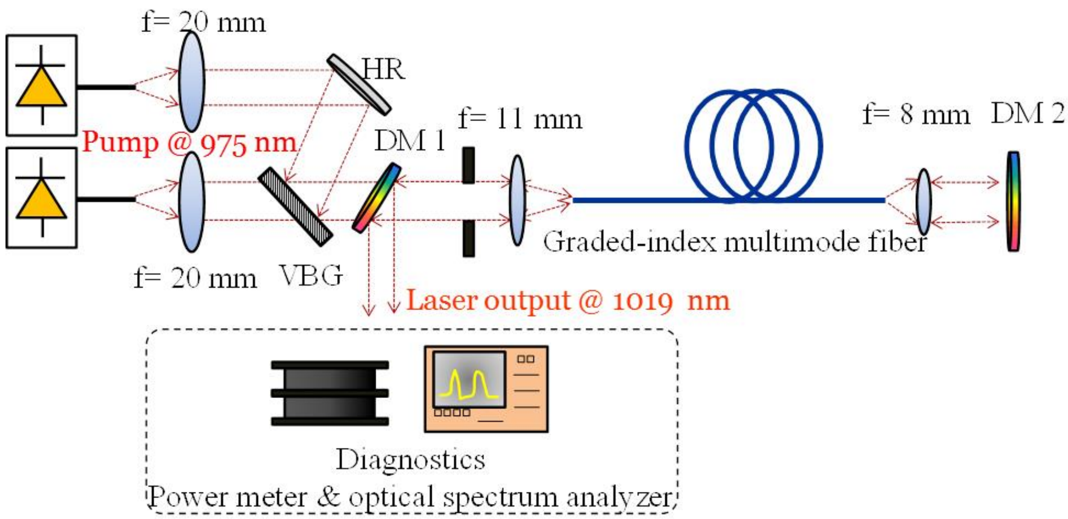

Fig. 1. Experimental setup for cw fiber Raman laser pumped directly by high-power, high-brightness diodes at 975 nm.

Pump source

The diode pump source comprised two multi-emitter diodes from IPG Photonics, each of which generated 45 – 50 W of output power at an NA of 0.12 from a 110 µm diameter core. These were wavelength-stabilized to slightly different wavelengths around 975 nm. The two diodes were spectrally beam-combined with a volume Bragg grating (VBG) with a bandwidth of 0.43 nm. The optical configuration for this is non-trivial, and requires some care in the analysis and implementation. We achieved a combined power of 70 W, so a radiance (brightness) of approximately 0.16 W sr^{-1} μm^{-2}.

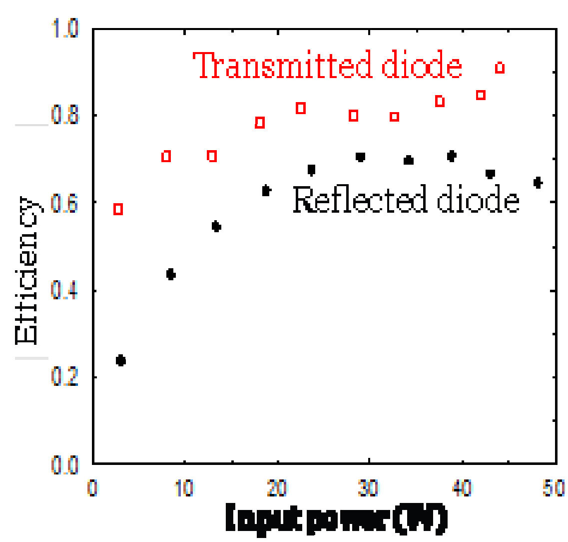

Fig. 2. Combination efficiency for reflected diode (circular spots) and transmitted diode (square spots) vs. input power.

This is very bright for a diode laser, but higher brightness will allow for considerably higher conversion efficiencies. Higher-brightness diode sources are becoming available. For example, polarization-combining can be used, and it would also be possible to wavelength-combine more of the IPG diodes, up

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to a pumping bandwidth of approximately 20 nm. Furthermore, companies such as TeraDiode and Direct Photonics already now provide higher-brightness diode sources. For example, Direct Photonics advertises a 500 W fiber-coupled laser with 20 nm linewidth and a radiance of 0.9 W sr^{-1} μm^{-2}. It may also be possible to achieve higher instantaneous power in the quasi-cw regime in, say, 100 µs pulses.

Fiber

We have primarily investigated two different fibers. One fiber is a commercial multimode fiber from OFS, with a 62.5 µm diameter, 0.275 NA graded-index germanosilicate core. The high NA implies that the Ge-concentration is quite high. A key attraction of this fiber is the low loss. The core propagation loss is measured to 1.7 dB/km at the pump wavelength (975 nm) and to 1.5 dB/km at the Stokes wavelength (1019 nm). These are very impressive losses at such high implied Ge-concentrations. However the MM nature of this fiber limits the beam quality.

The other fiber is a double-clad germanosilicate fiber, fabricated in-house, with designation A0413-L10284. The refractive index profile of the preform is shown in Fig. 3. This was drawn to a fiber with inner-cladding diameter of 38 µm and core diameter of ~ 14 µm. The inner-cladding NA is ~ 0.3, and the core NA ~ 0.1. There is a pronounced dip in the index profile, which is likely to affect the guiding properties to some, relatively small, degree.

This high Ge-concentration is one attraction of this fiber. Apart for the high NA, the high Ge-concentration also leads to a high Raman gain coefficient, estimated to 2.6×10^{-13} m/W. This is five times as high as that of standard single-mode fiber at 1060 nm.

The inferred Ge-concentration is ~ 35% higher than in the commercial OFS fiber, which is good, but unfortunately the loss is also higher, by a considerable amount. We measured the loss to 7.4 dB/km at 975 nm. See Fig. 4.

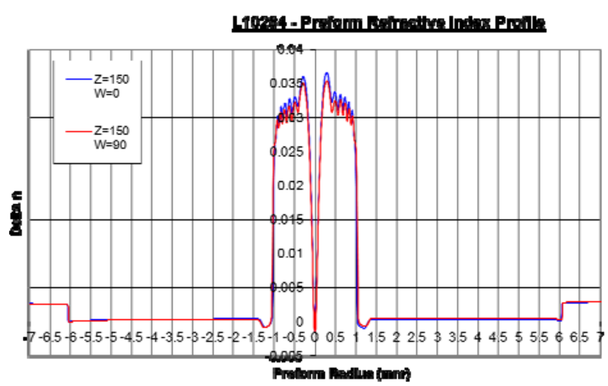

Fig. 3. Refractive index profile of preform of double-clad Raman fiber (A0413-L10284) in two orthogonal directions.

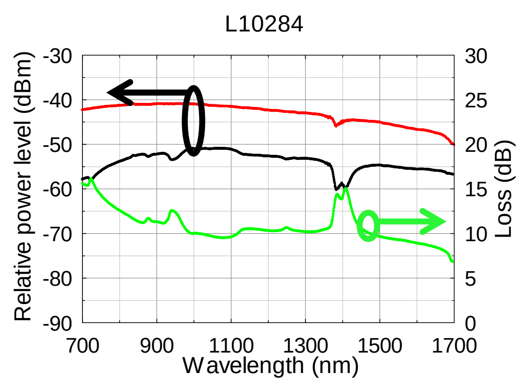

Fig. 4. Spectra of transmitted light for fiber A0413-L10284 of lengths 650 m and 5 m, and the difference (loss), corresponding to a length of 645 m.

Experimental results

OFS fiber

The OFS fiber behaved very well. Two lengths of fiber were used, 3 km and 1.5 km, giving effective lengths of 1.8 km and 1.1 km, respectively. In the far end of the fiber, a lens-coupled dichroic mirror with reflectivity over 99% for both of pump and signal, was used to launch escaping light back into the fiber

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with 80% launch efficiency. The dichroic mirror also helps to prevent unwanted conversion to higher Stokes order, thanks to a high transmission for wavelengths longer than the 1st Stokes. The fiber had flat normal cleaves in both ends. Thus, the resulting 4% reflectivity closed the laser cavity and provided outcoupling in the pump launch end, where a dichroic mirror was used to separate the outcoupled beam from the pump path. The total signal roundtrip loss becomes 19.5 dB and 17.3 dB for the two different fiber lengths.

The total laser output powers for 3 km and 1.5 km long fiber are shown in Fig. 5, alongside with the results of numerical simulations which show good agreement. The output power with 3 km long Raman fiber reaches 15 W with a slope efficiency of 62%. For 1.5 km long fiber, an even higher slope efficiency of up to 80% is achieved, while the highest output power is as high as 20 W. This corresponds to a record optical-optical device efficiency of about 50%. Fig. 6 shows an optical spectrum (2 nm resolution) at highest output level, The output spectrum is free from any higher order Stokes light.

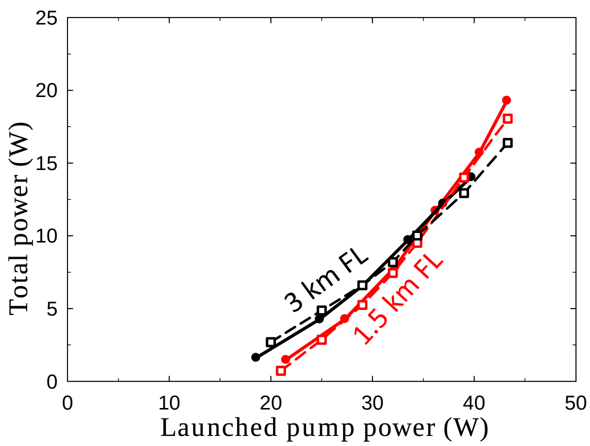

Fig. 5. Experimental FRL output power for OFS fiber (circular spots, solid line) and simulated output power (square spots, dashed line).

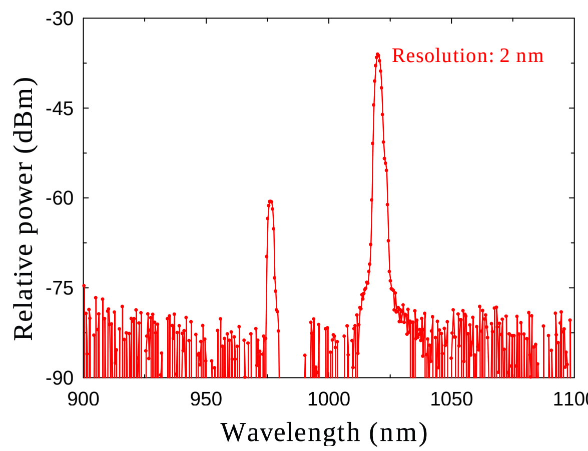

Fig. 6. Experimental FRL output spectrum at 20 W output power using 1.5 km of OFS fiber.

Moreover, we measured the beam quality of the launched pump and output signal and found that the beam propagation factor (M^2) of pump and signal at highest power level are 22.2 and 5.0 respectively. The improvement is expected as SRS in GRIN-MM fibers is known to improve the beam quality [4].

Further performance improvements are possible with a more precise optimization of fiber length while balancing optical background losses and better output coupling. Shorter devices lead to an increase of the threshold and necessitate the use of higher pump power in order to achieved good conversion efficiency. This can be addressed with a higher reflectivity of the output coupling end.

An analytical solution for modeling the laser configuration used exists [5]. This makes it possible to obtain the optimal parameters, such as the fiber length and the output cavity reflectivity to get the maximum laser power and conversion efficiency. This is shown in Fig. 7, which also shows the corresponding maximum output power. Although the 3.5% - 4% output coupling we used isn't optimum, the reduction in power is quite small and the precise value of the reflectivity is not critical. A somewhat shorter optimal fiber length, ~1 km, than the 1.5 km we used is also indicated. However given the similar results obtained with 3 and 1.5 km long fiber, the effect of this reduction in fiber length is expected to be small.

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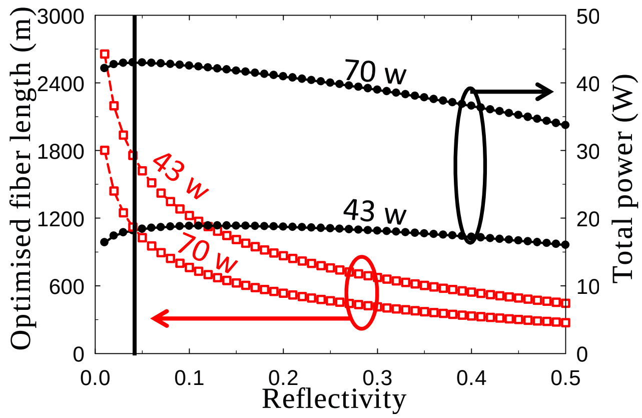

Fig. 7. Analytical calculation of optimum OFS fiber length (squares, dashed curve) and output power (circles, solid curve) *vs*. output reflectivity, for 43 W and 70 W of pump power.

Double-clad Raman fiber A0413-L10284

Because of the higher loss and shorter fiber length (~ 645 m, effective length ~390 m), it was not possible to reach laser threshold with the configuration in Fig. 1. This was therefore modified to use a 60% reflecting output coupler, rather than just relying on the 4% feedback of the perpendicularly cleaved fiber end as depicted in Fig. 1

The lower output coupling and the higher background loss than in the OFS fiber reduces the slope efficiency to ~18% (Fig. 8). The beam quality improves to $M^2 = 2$.

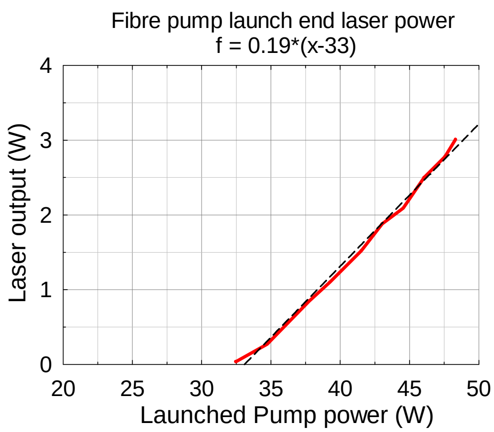

Fig. 8. Experimental FRL output power for DCRF A0413-L10284.

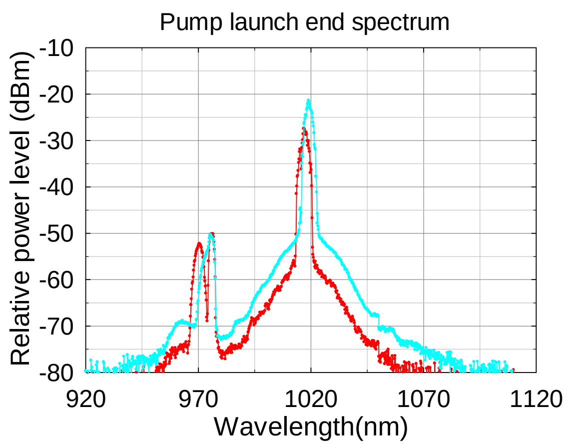

Fig. 9. Experimental FRL output spectrum for DCRF A0413-L10284 at two different output powers.

The results will be published / presented at ASSL in October 2013 [6].

4 (A). Conclusions

These results are very exciting breakthroughs.

- 80% slope efficiency
- 20 W output power

  - First demonstration > 1 W of any directly diode-pumped fiber Raman device
  - Scalable to much higher power
    - Suitable multi-kW diode pump sources are now becoming available from TeraDiode and Direct Photonics
- 10x brightness enhancement in GRIN-MM fiber
- First demonstration of a double-clad Raman fiber laser directly cladding-pumped by diodes
- The 835 nm synchronously pumped FRL is the shortest-wavelength directly diode-pumped FRL of any description and represents a large extension of the wavelength coverage of this emerging technology.

We also have results on narrow-line fiber Raman amplifiers but are not yet ready to report those.

Next steps

Power scaling and improved efficiency are the next steps. Reducing the propagation loss then seems like an obvious step, and something we will pursue. However higher pump power is more important. Higher pump power is a prerequisite for substantial power scaling, and will, by virtue of a higher Raman gain per unit length, lead to shorter fibers in which the loss becomes less important. Even the relatively high loss of 7.4 dB/km can be acceptable with the five times higher pump brightness that is now commercially available. Therefore, approaches that lead to a better beam quality seems more important than lower fiber loss.

High-power, high-brightness pump sources are expensive. We do plan to pursue that approach, but in the nearer term we intend to see if higher instantaneous powers can be reached in the QCW regime.

Part B, Power and efficiency scaling of fiber OPO around 700 to 850 nm

2 (B). Approach and objectives

We have worked on this topic intermittently for five years, initially under EOARD FA8655-08-1-3013. The purpose is to realize a high-power efficient narrow-line source (i.e., a fiber OPO), which can be pumped by a Yb-doped fiber MOPA and convert the pump power into the visible / NIR. Though this is general-purpose technology, our targeted application was pumping of alkali lasers, amongst a large range of exciting applications. The work has resulted in several publications and a PhD thesis (Gysbert van der Westhuizen) [7].

In our work under FA8655-08-1-3013 [8] we found that the threshold is undesirably high, and we therefore wanted to use a longer parametric gain fiber (up to 100 m) to both reduce the threshold and convert power more efficiently. At the same time, we wanted to use spectral filters to reduce unwanted nonlinear scattering (in particular stimulated Raman scattering, SRS). These were the objectives of the continuation work under FA8655-11-1-3088.

3 (B). Results, findings, accomplishments

The setup, comprising the pulsed Yb-doped fiber MOPA timed for synchronous pumping and the fiber OPO is shown in Fig. 10. The fiber OPO emits anti-stokes (AS) radiation at around 718 nm when pumped at around 1080 nm. A more thorough description of the context and a large number of results are presented in Gysbert van der Westhuizen's thesis [7], which is available online. See, e.g., Section 5.4.2.

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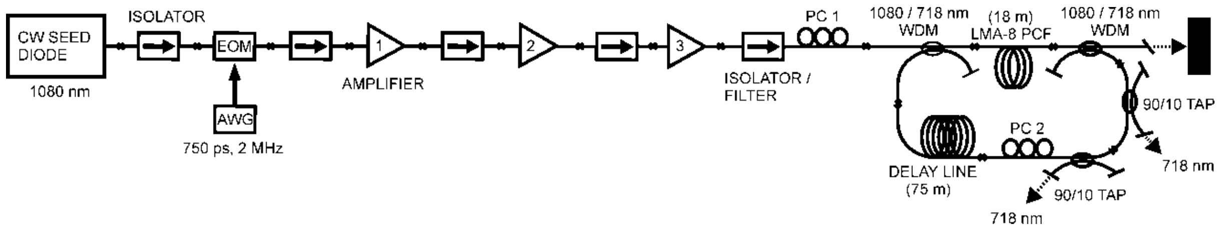

Fig. 10. Fiber OPO setup, including Yb-doped fiber MOPA pump source.

Figure 10 shows the delay line to be 75 m long and the parametric gain fiber (PGF) to be 18 m long. The PGF was an air:silica micro-structured fiber, LMA-8 from NKT Photonics. However these lengths (in particular the PGF) were changed in order to try to improve the fiber MOPA. The resulting AS power at ~ 718 nm, together through the two output ports, is shown in Fig. 11, for a total outcoupling in the two tap couplers of 19%. The threshold is highest for the shortest PGF (11 m), but then similar, ~400 W, for fiber lengths of 18 m or more. This power is probably too high for cw operation. Although the threshold can be expected to be lower with cw pumping than it is with pulsed pumping, many of the fiber components used seem unlikely to be able to handle the threshold power for cw operation.

Figure 11 also shows that the efficiency decreases for PGFs longer than 35 m.

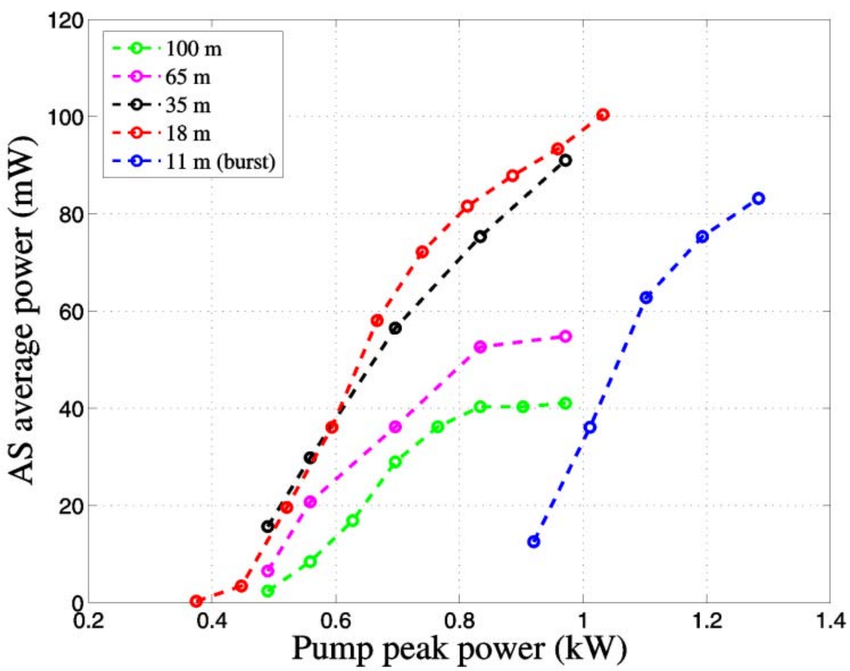

Fig. 11. Total AS output power from two output ports vs. pump power for different PGF lengths. The low average power is due to the low duty cycle. From [7].

Some experiments were undertaken to improve the OPO using spectral filters that suppressed SRS from the AS at ~ 718 nm. See [7] (Section 5.4.3). Success was mixed. While it is important to suppress SRS from the AS at high powers, in order to improve conversion efficiency and spectral purity, it is not important for the threshold, since the AS power is then too low to generate SRS. The threshold was our

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first priority, and our work therefore focused on that, and in particular why the gain and thus the threshold did not scale with PGF length the way we had hoped.

There are several possible reasons for this, including walk-off, pump linewidth broadening, and longitudinal fluctuations of the properties of the parametric gain fiber.

Influence of pulse duration

Of the possible reasons for the low gain, several depend on the pulse duration. This includes walk-off We did not measure the walk-off directly, but have calculated a walk-off rate of 23 ps/m between pump and AS, 46 ps between pump and Stokes, and 23 ps between AS and Stokes waves. The pump wave travels with highest group velocity. See [7], Fig. 5.14. Given that we used ns-scale pulses, walk-off can be expected to be a factor for fiber lengths of 100 m. However, while the walk-off is quickest for the Stokes wave, this is relatively readily replenished (with the right phase for the desired FWM), and need not be detrimental. This complicates the overall interpretation, and calls for detailed simulations with a precise description of the longitudinal fluctuations of the fiber. This was not available. Still, also the pump – signal walk-off is sufficiently fast to be a factor. Fig. 12 shows the influence of pulse duration for fiber lengths of 18 and 35 m, for different pulse durations. For the longer fiber, both of the shorter pulse durations, 800 ps and 530 ps, seem too short for walk-off to be avoided, since they both result in thresholds that are higher than with 1330 ps pulses.

It can be shown that in the walk-off limited regime, under certain assumptions, the thresholds for different pulse duration correspond to constant pulse energy [9]. It is not obvious how to extrapolate the curves in Fig. 12 to the threshold, but it may be around 700 W or 0.37 µJ for 530 ps pulses and 450 W or 0.36 µJ for 800 ps pulses in the 35 m long gain fiber. A 35 m long fiber would have a pump – signal walk-off of, roughly, ~ 805 ns. The error margins are substantial, but this data still suggests that we are in a walk-off limited regime.

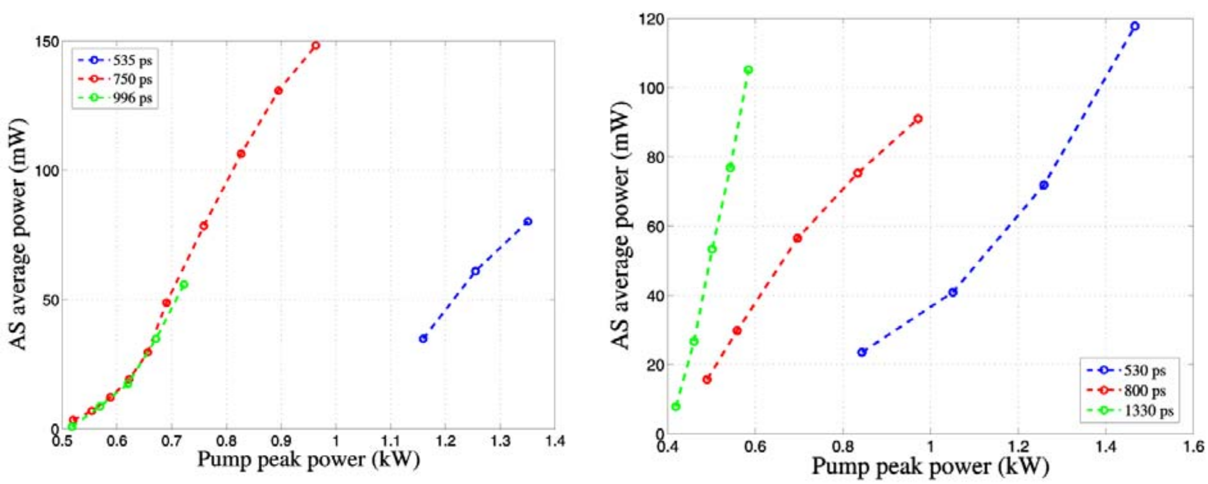

Figure 12. Anti-Stokes average power, as a function of pump peak power, for three values of the pump pulse width, for the cases of 18 m (left) and 35 m (right) of PGF. From [7]

In the walk-off limited regime, a longer fiber won't help to reduce the threshold for a particular pulse duration. However, it does allow us to use longer pulses, e.g., to reach a lower peak power threshold. Unfortunately, we quickly ran into unwanted stimulated Brillouin scattering (SBS) from the pump. The Brillouin threshold decreases quickly with pulse duration and prevented us from using pulses longer than ~ 1.5 ns. While the pump linewidth can in principle be broadened to suppress SBS, our pump source did

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not have that capability. This also limited our ability to investigate the direct impact of the pump linewidth on the parametric conversion (i.e., unrelated to SBS). Although theoretical analysis suggested that our pump linewidth was sufficiently narrow for efficient pumping of the parametric conversion, this was less clear from experiments and would have warranted further investigations. In particular, SPM is expected to spectrally broaden the pump pulses as they propagate through the PGF. If the linewidth becomes larger than the pump acceptance bandwidth after some distance then this limits the effective length of the PGF. Shorter pulses normally lead to more spectral broadening. However we were unable to investigate this directly.

OTDR measurements

Even an effective length of, say, 10 m (if that's the walk-off length) would still allow for a threshold well below 100 W, i.e., much lower than we measured. To better understand why this is the case, we investigated how the pulse energy evolved in the PGF, by measuring the back-scattered AS light as a function of time. Measuring back-scattered light in this way maps the fiber position onto time, just as in optical time domain reflectometry (OTDR).

We believe this is the first time that the pulse energy evolution and thus the gain has been measured in this way. We found it to work quite well, after some optimization regarding detector selection, oscilloscope, and (optionally) RF amplifier. The power backscattered from the fiber was estimated to around 15 nW. We were even able to measure single-shot traces. See Appendix for examples of OTDR traces. Still, the optimization was far from exhaustive, and further optimization should significantly improve the sensitivity and the resolution (which can be traded against each other). In contrast to the previous results, these results have not been reported in [7] or anywhere else.

The ability to see how the pulse energy evolves is a great help for the optimization and analysis of the conversion in the PGF. It is bound to make a real difference, and one really should not attempt this kind of work without this type of setup, or something equivalent.

Figure 13 shows the pulse energy evolution and gain per unit length for different pulse durations. Several things are apparent. The pulse energy initially grows approximately exponentially. After some distance the graph indicates an approximately linear increase. However it is not clear to what extent this linear increase corresponds to an increase in pulse energy, since the RF amplifier (MITEQ AU-1310) was AC-coupled with 10 kHz cutoff frequency, i.e., with a time constant of 10 μs. This suggests that recovery would occur at a rate of 1% over 100 ns, whereas the graphs shows a rate of change which is of the order of 10% over 100 ns, in the quasi-linear section of the curve. This does indicate that the recovery rate of the AC-coupled amplifier only accounts for a small fraction of the change, and there is after all an approximately linear increase in pulse energy which accounts for the remainder. An increase in energy would not be surprising, but should be verified with a DC-coupled system (alternatively the response of the RF amplifier could be more carefully characterized and compensated for).

The exponential growth lasts longer for longer pulses. This could be because of the longer walk-off length. However, our analysis of the dispersion in this fiber suggests that the walk-off should be smaller than Fig. 13 indicates. As mentioned above, an alternative explanation is that the larger linewidth and linewidth broadening (due to the higher peak powers) of the shorter pulses causes the pump linewidth to exceed the pump acceptance bandwidth, but this has not been verified.

In addition, the gain in the initial part of the PGF is only around 10% of what it would be in the ideal case. Possible explanations include fiber fluctuations and the pump linewidth, although the linewidth is sufficiently narrow (at least in the initial part of the fiber), according to our analysis,

More careful analysis and measurements are needed to fully establish why the gain is lower than ideal in the initial part of the fiber, and why it drops even further in the latter part.

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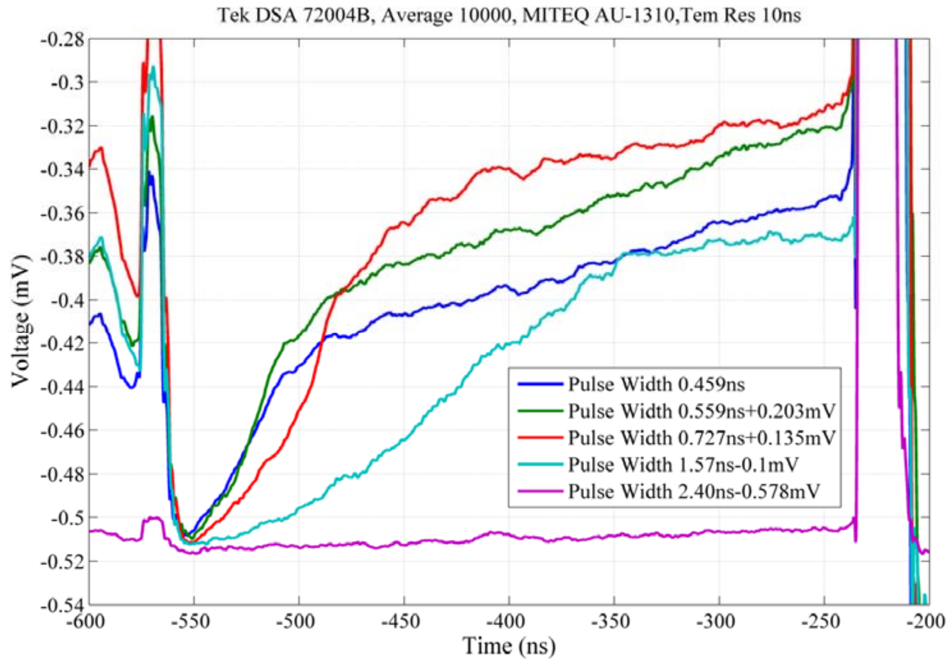

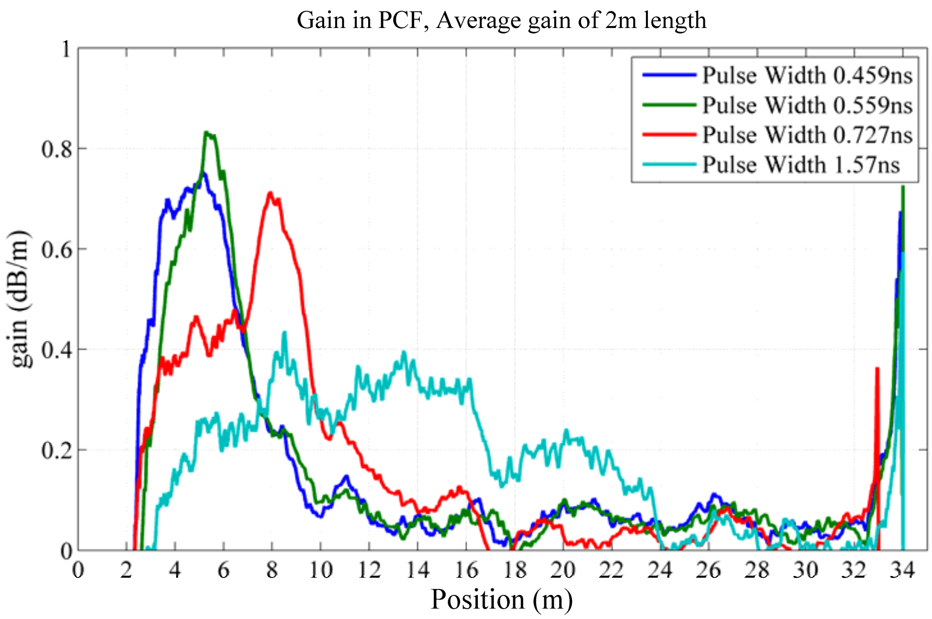

Figure 13. OTDR traces of the AS (top) and calculated gain (bottom) in a ~35 m long PGF for different pulse durations. A Thorlabs DET02AFC biased silicon detector was used for the OTDR. The temporal resolution is ~ 10 ns. 1 ns in the OTDR trace corresponds to ~10.3 m of fiber. In all cases the integrated gain must equal the cavity loss of ~ 8 dB.

Longitudinal fiber control through heating – preliminary attempts

The OTDR measurement system is very useful in diagnosing problems, and can also be used for online optimization. We attempted this by heating sections of the PGF. This changes the dispersion properties, so can be expected to modify and ultimately improve the conversion.

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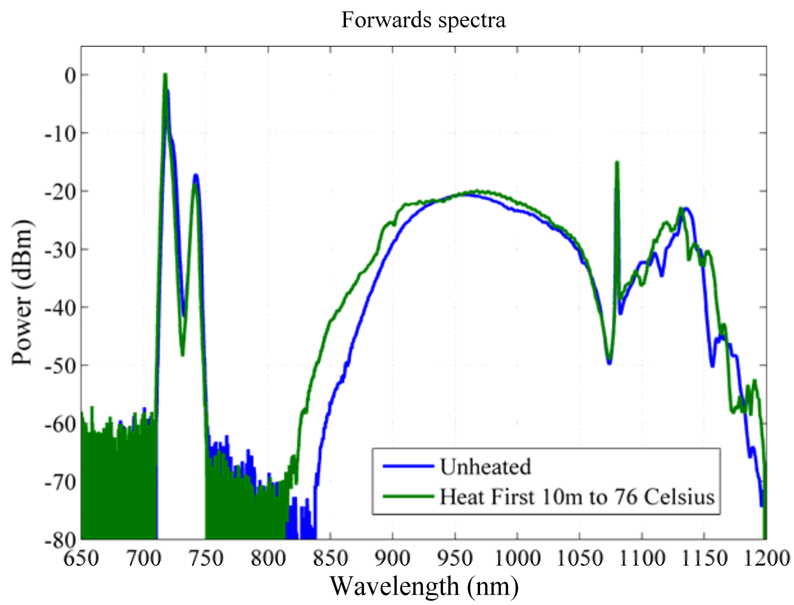
The first 10 meters of the PGF was immersed in a water bath and its temperature raised to 76ºC. The rest of the PGF (~24 m) remained at room temperature (~22 C). After heating, the PRF of the pump pulses was adjusted slightly to maintain synchronous pumping. The period changed from 541.79 ns (unheated) to 541.93 ns (heated).

The output spectrum changed somewhat upon heating (Fig. 14), and the output power decreased marginally. There was also a marked decrease in the conversion at the transition between the heated and unheated part of the fiber (Fig. 15). More investigations are needed in order to determine if and by how much the conversion can be improved by controlling the dispersion in this way, and what longitudinal resolution would be needed.



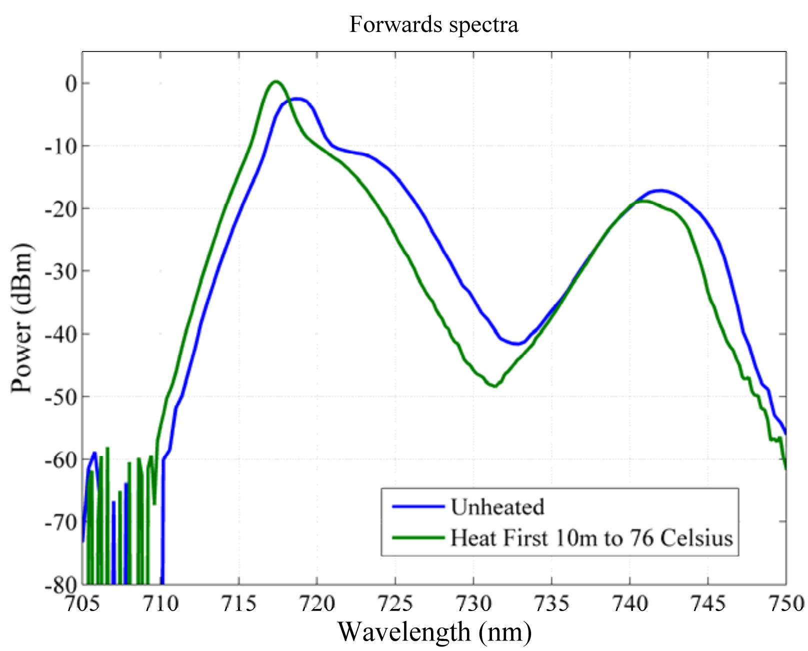


Figure 14. Fiber OPO output spectra over a wide spectral range (top), and zoomed in to show the details of the AS peak as well as SRS at 740 nm (bottom). The two curves are for the whole PGF at room temperature (blue) and for the first 10 m heated to 76ºC (green).

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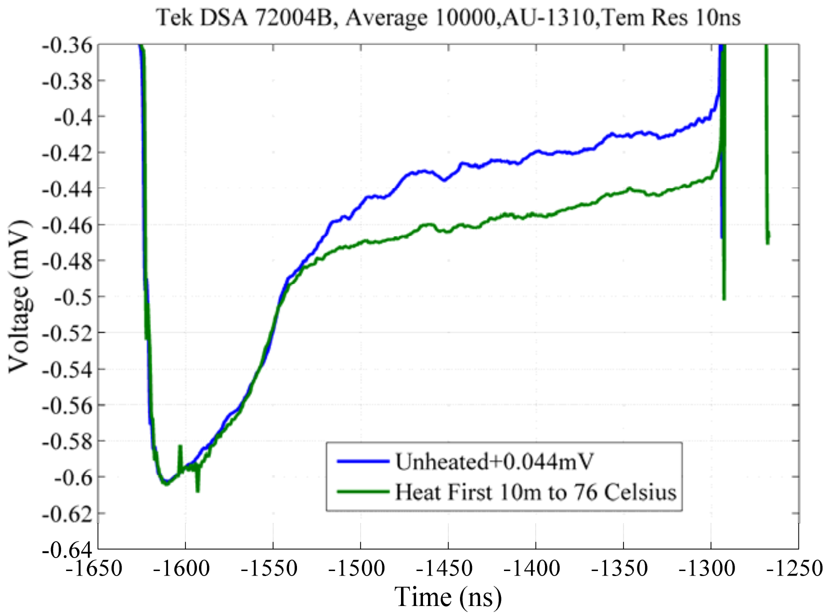

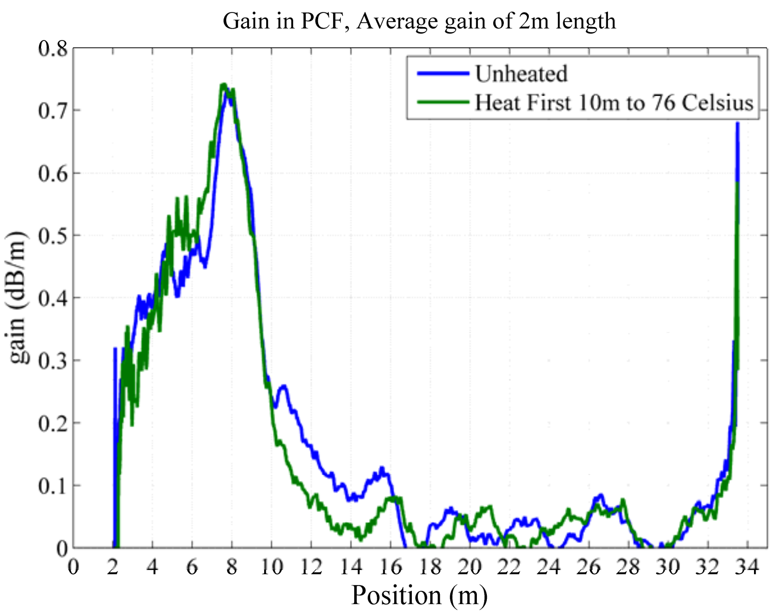

Figure 15. OTDR traces of the AS (top) and calculated gain (bottom) in a ~35 m long PGF. Temporal resolution ~ 10 ns. The two curves are for the whole PGF at room temperature (blue) and for the first 10 m heated to 76ºC (green).

4 (B). Conclusions

This was a six months' effort that in the first instance aimed at investigating whether a simple replacement of the PGF with a longer one would reduce the threshold and / or improve the efficiency. We found this was not the case and then went on to develop diagnostics to investigate why. Preliminary attempts to improve the conversion by heating a section of the PGF to modify the dispersion along the fiber were not successful, although we did see that the dispersion did change in the heated section.

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- PGFs longer than 35 m were not helpful for improving threshold or efficiency
- Only the initial part of the PGF contributed efficiently to the gain and power conversion.
- Even in the initial part, the gain was only around 10% of what it would be in the ideal case.
- To determine the gain distribution, we built unique diagnostics that can show how the power builds up along the PGF. We believe this is for the first time and we view it to be a very useful development.

There is every reason to think that the problem is longitudinal variations in the PGF. These perturb the phase-matching and prevent efficient power conversion. Walk-off is also a factor for short pulses in long PGFs, with the pulses we used.

Although we were not able to overcome the problem of low gain and high threshold, this is very much preliminary work, and we have identified several routes forward. Key is our new ability to measure the AS power evolution in the fiber. Thus, while the threshold is still too high to consider cw-pumping our fiber OPO, further reductions in threshold to enable this also for wavelengths in the red should be possible.

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2. Tianfu Yao and Johan Nilsson, “An 835 nm fiber Raman laser pulse-pumped by a multimode laser diode at 806 nm”, JOSA B, accepted for publication

3. Tianfu Yao and Johan Nilsson, “Fibre Raman laser directly pumped by multimode laser diode at 975 nm”, CLEO Europe, Munich, Germany, May 12-16 2013, paper CJ-9.2

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5. Personnel

Principal Investigator: Johan Nilsson (professor)

Co-investigator on Raman work: Jayanta K. Sahu (professor & head of silica fiber fab)

Additional personnel: Gysbert van der Westhuizen (PhD student), Han Kai (visiting PhD student), Hoon Jeong (visiting research fellow), Tianfu Yao (PhD student), Harish Achar Vasant (PhD student), Andrew Webb (senior fiber development engineer, silica fiber fab)

Of these, J. Nilsson and G. van der Westhuizen have been directly supported, whereas J. Sahu and A. Webb are supported through fiber fabrication charges. Other personnel have been supported through payment of indirect charges.

6. Publications

Tianfu Yao and Johan Nilsson, “Short-wavelength fiber Raman laser pulse-pumped by multimode laser diode at 806 nm”, in Advanced Photonics Congress, OSA Technical Digest (online) (Optical Society of America, 2012), paper STu4F.4 (Specialty Optical Fibers 2012)

Tianfu Yao and Johan Nilsson, “Fibre Raman laser directly pumped by multimode laser diode at 975 nm”, CLEO Europe, Munich, Germany, May 12-16 2013, paper CJ-9.2

Tianfu Yao and Johan Nilsson, “High power, high efficiency fiber Raman laser pumped by multimode laser diodes at 975 nm”, ASSL 2013, paper ATu1A.4

Tianfu Yao and Johan Nilsson, “An 835 nm fiber Raman laser pulse-pumped by a multimode laser diode at 806 nm”, JOSA B, accepted for publication

G. J. Van der Westhuizen and J. Nilsson, “All-fibre OPO system for visible wavelengths”, in Proceedings of the International Quantum Electronics Conference and Conference on Lasers and Electro-Optics Pacific Rim 2011, (Optical Society of America, 2011), paper C988, p. 226-228

G. J. van der Westhuizen, *Fibre optical parametric devices for large frequency-shift wavelength conversion*, PhD Thesis, University of Southampton (2012)

7. Interactions and Transitions

Coverage: (a) participation/presentations at meetings, conferences, seminars, etc., (b) consultative and advisory functions to other laboratories and agencies, and (c) transitions.

The results have been presented at a large number of meetings, seminars, etc.

<u>CLEO Pacific Rim, Sydney, Australia, Aug 28 – Sep 1 2011 (G. J. van der Westhuizen)</u>

G. J. Van der Westhuizen and J. Nilsson, “All-fibre OPO system for visible wavelengths”, in Proceedings of the International Quantum Electronics Conference and Conference on Lasers and Electro-Optics Pacific Rim 2011, (Optical Society of America, 2011), paper C988, p. 226-228.

<u>Advanced Solid State Photonics, San Diego, CA, Jan 29 – Feb 1 2012 (J. Nilsson)</u>

J. Nilsson, “High power fiber lasers: fundamentals and frontiers” in Lasers, Sources, and Related Photonic Devices, OSA Technical Digest (CD) (Optical Society of America, 2012), paper AT1A.1 (ASSP 2012, invited).

<u>Specialty Optical Fibers, Colorado Springs, CO, June 17 – 20 2012 (T. Yao)</u>

Tianfu Yao and Johan Nilsson, “Short-wavelength fiber Raman laser pulse-pumped by multimode laser diode at 806 nm”, in Advanced Photonics Congress, OSA Technical Digest (online) (Optical Society of America, 2012), paper STu4F.4 (Specialty Optical Fibers 2012).

<u>International Conference on Development and Application of High Power Fiber Lasers, Chengdu, China, April 2012 (J. Nilsson)</u>

Presentation, "High-power fiber lasers: Recent developments and new challenges".

Photonics West, San Francisco, CA, Jan 2012 (J. Nilsson)

Presentations at Sandia National Labs (host D. B. S. Soh) and Lawrence Livermore National Labs (host J. Dawson). Participation in conference.

Korea, April 2012 (J. Nilsson)

Seminars at Samsung Advanced Institute of Technology in Giheung, Gyeonggi-do, Samsung Fiberoptics, Gumi, Gyeongsangbuk-do, and EO Technics, Anyang, Gyeonggi-do.

8. New discoveries, inventions, or patent disclosures (if none, report none.)

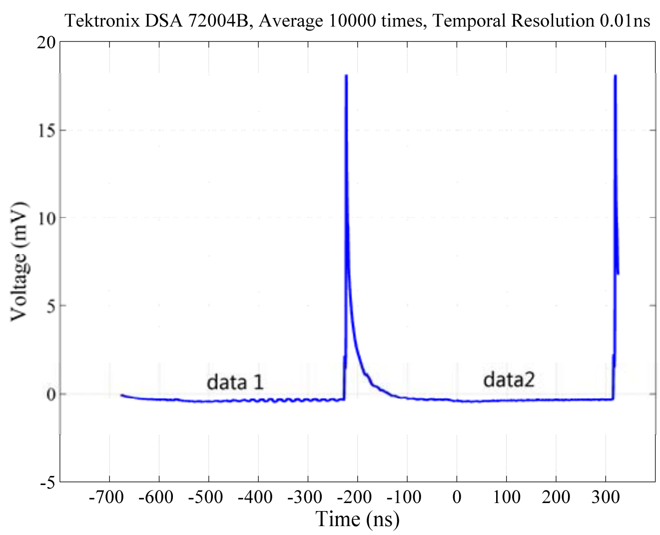
None.

9. Honors and awards

None

Appendix: Examples of OTDR traces of pulses amplified in the fiber OPO

The OTDR trace is dominated by reflections from splice points& terminations. These are not relevant and should be discarded. In this case the interesting data is approximately in the range 100 – 300 ns.



Attention to detail is necessary

Data is zoomed and averaged off-line to reveal the interesting part of the spectrum. These are some early, poor traces with inadequate detectors. The parametric gain fiber starts at ~ 120 ns.

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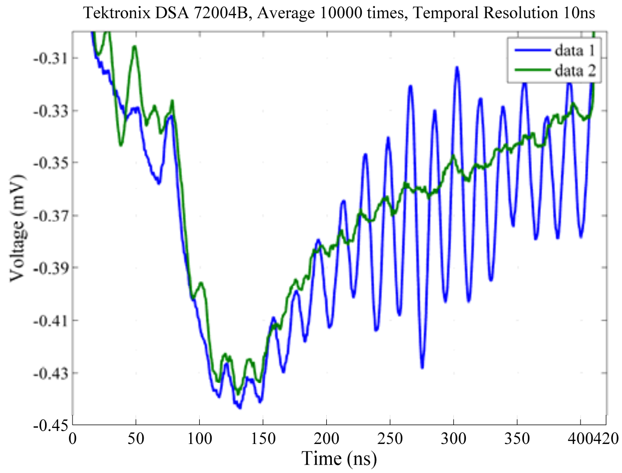


Oscilloscope

A few different oscilloscopes were tried. We ended up using one low-speed and one high-speed oscilloscope in parallel for the duration of these measurements.

The low-speed oscilloscope was an Agilent DSOX2022A for ~ $2,000. The bandwidth of 200 MHz was perhaps inadequate (though not by much given that our pulse duration is ~ 1 ns, or possibly down to 100 ps), but it was still very useful thanks to its low noise and high amplitude resolution (0.1 mV).

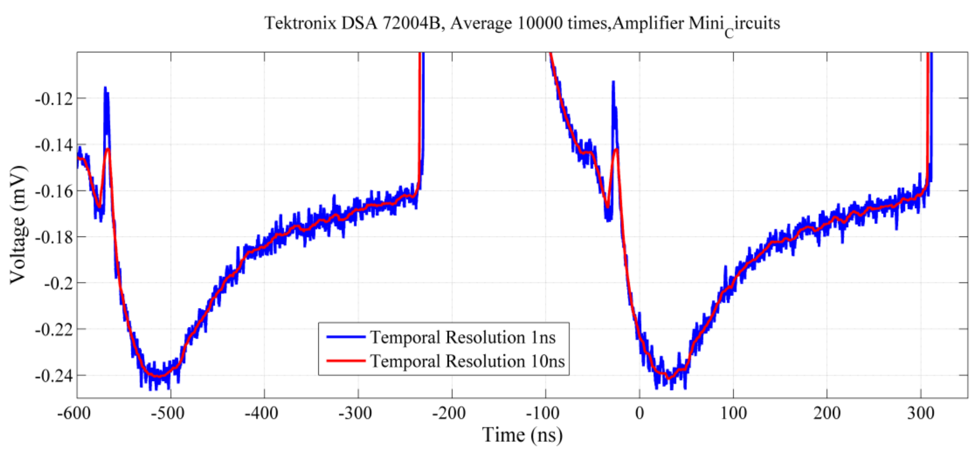
The high-speed scope was a Tektronix DSA 72004B (list price ~$160,000). The bandwidth of 20 GHz is far more than required. The noise seemed higher than that of the Agilent oscilloscope (when compensating for the bandwidth).

An oscilloscope of 0.5 – 1 GHz bandwidth seems best for this work. The required sensitivity depends largely on the RF amplifier, which we normally found to be necessary.

RF amplifier

Three different RF amplifiers were used. These were chosen amongst existing amplifiers, but a review of available amplifiers did not find any which was obviously significantly better.

Mini-Circuits ZFL-500LN+, 0.1 – 500 MHz. This is OK, but the relatively high low-frequency cutoff appears to partly distort the trace.



Trace with Mini-Circuits ZFL-500LN+ RF amplifier, showing the continuous increase of power towards the output of the fiber in the range 150 – 300 ns. Fiber extends from ~ 0 ns to ~ 300 ns.

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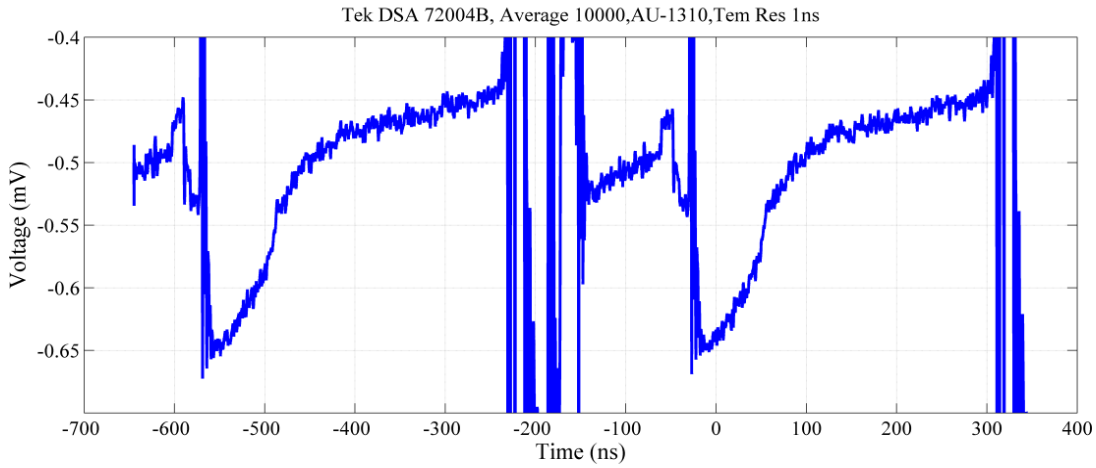
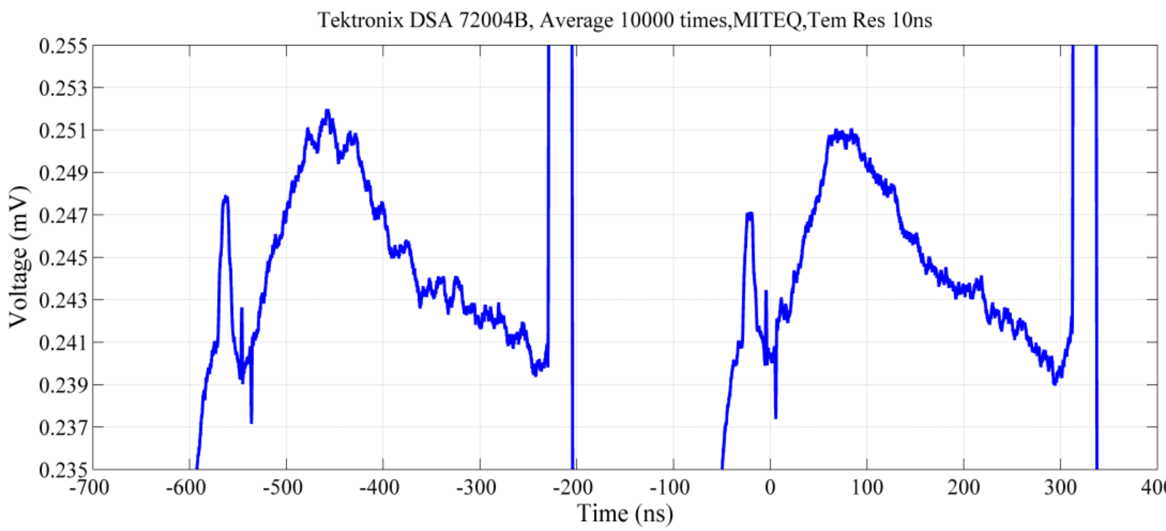
MITEQ AU-1310, 0.01 – 500 MHz. This was used most of the time. It seemed to have the fastest response, but suffered somewhat from the finite low-frequency cutoff.



Trace with MITEQ AU-1310 RF amplifier. Fiber extends from ~ 0 ns to ~ 300 ns.

MITEQ 2D-005040-29-15P, DC – 500 MHz. This is attractive because of the absence of low-frequency cutoff, but the trace exhibited significant distortions.



Trace over two periods with MiniMITEQ 2D-005040-29-15P RF amplifier. Fiber extends from ~ 0 ns to ~ 300 ns. In particular the decrease from 100 ns to 300 ns is unexpected and assumed to be in error.

We also tried an Amplica Inc. 401PSL, but the bandwidth was apparently limited to 100 MHz, which we considered to be too low.

Detector

The detector is arguably the most critical part of the system. Low noise and sufficient bandwidth are both critical. In the end we used two detectors.

Thorlabs DET02AFC, biased silicon detector, bandwidth 1.2 GHz, NEP 9.5 fW $Hz^{-1/2}$.

Thorlabs APD 110A/M, avalanche photodetector, silicon, bandwidth 50 MHz, NEP 160 fW $Hz^{-1/2}$.

The advantage with the APD is that no RF amplifier is needed. It is also DC-coupled. The low bandwidth is a disadvantage.

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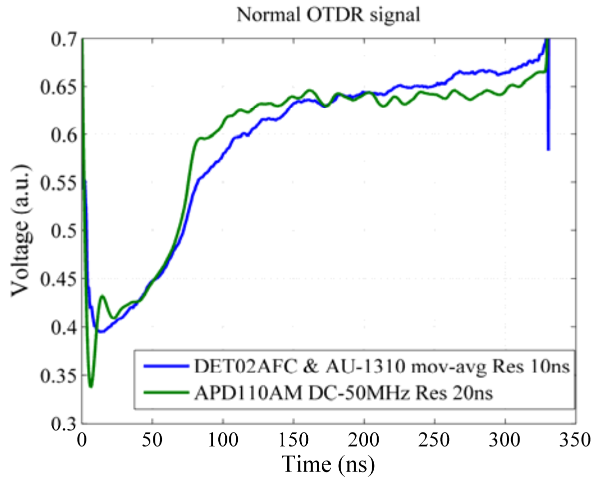
Hamamatsu offers APDs with higher bandwidth, but noise is an issue.



Comparison between OTDR traces from APD110A/M and DET02AFC with MITEQ AU-1310 amplifier. The increase at the end of the DET02AFC trace is caused by the non-zero lower cut-off frequency of the amplifier.

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